ON THE EFFECT OF GASEOUS ENVIRONMENT ON CRACK PROPAGATION *

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A wide variety of the mechanical properties of materials are affected by the presence of gaseous environments. Active gaseous environments can significantly reduce the ductility and strength at fracture of materials ranging from glass through ceramics to metal single crystals[1,6]. The understanding of such effects is fundamentally important and of practical interest in applications such as the selection of materials for space vehicles where components are exposed to large changes in temperature and pressure.

The influence of an active gas on a material under stress is generally attributed[1,2,3,4] to sorption of the gas at the tips of cracks which are produced either by the deformation or by the method of forming the material. This sorption of gas at the tips of cracks weakens the material and enhances the rate of crack propagation. It has been pointed out[2], however, that the influence of an active gas is hard to explain because even at low gas pressures the high molecular speed suggests that gas molecules can reach and saturate the freshly exposed material at the crack tip in relatively short times, i.e., far shorter times than those involved in the application of stress to the material.

My purpose here is to show that the average molecular velocity when used in this manner is not always the best indication of the time for molecules to reach the crack tip, since this time is determined by the crack

geometry and the type of gas flow at the gas pressure concerned, i.e.,
whether the flow is viscous, free-molecular or in the transition range.

The approximate limits to the pressure regions, in which the
different types of gas flow occur, are given[5] by the Knudsen number, i.e.,
the ratio of the mean free path of the gas molecules in a channel and the
characteristic dimension of the channel, α, such as its diameter. The
following discussion is confined to the range in which free-molecular flow
occurs, i.e., for Knudsen numbers greater than one, or alternatively this
may be expressed[5] for air at 25°C as $\alpha \cdot P < 5 \times 10^{-3}$, where P is the
pressure in mm Hg and α is the characteristic dimension in cm. The
importance of free-molecular flow is twofold. Firstly, for small cracks,
α is small so that this type of flow can occur up to high pressure, e.g.,
for $\alpha \simeq 10^{-5}$ cm free-molecular flow will occur up to $P \simeq 5 \times 10^{2}$ mm Hg.
Secondly, for free-molecular flow, the transport of gas molecules along a
channel is severely restricted when the cross-section of the channel is small[5,10].
This second feature has been shown[?] to be consistent with the gas pressure
dependence of the thermal conductivity of two-phase systems of gas and uncon-
solidated glass bead pacts where the pore space is small compared with the
radius of the bead and the mean free path of the gas molecules. Examples
of small cracks, which can affect the mechanical properties in the presence
of an active gas, are: fatigue cracks[2,3], cracks in oxide films[6], cracks in
brittle materials[1,7] produced by handling or the method of preparation, and
cracks produced by static fatigue[4].

One of the important parameters in determining the influence of
an active gas on the mechanical properties of a material containing a
small surface crack is the time for the formation of a unimolecular layer

on the walls of the crack. This time, t_1, is now estimated for free-molecular flow conditions using Clausing's "gas capillary" model[8] which assumes that the walls of the crack are initially clean, that the unimolecular layer is first formed at the mouth of the crack and spreads along its length, that once the unimolecular layer has formed no further adsorption takes place, and that the shape of the crack can be approximated by a channel of uniform cross-section. Under these assumptions, one can write, if the boundary of the adsorbed layer which has reached a position x along the crack in time t, such that $0 < t < t_1$ and $0 < x < \ell_1$, grows a distance dx in time dt:

$$K'A \, \nu_1 \, dt = \frac{H \, dx}{f} \qquad \qquad \dots \dots \quad (1)$$

where A is the cross-sectional area of the crack, H the perimeter of the crack, f is the cross-sectional area of the gas molecule, and ν_1 is the number of molecules striking unit area per sec. at the surface of the material. K' in equation (1) is[5] the ratio between the rate at which gas ... at a position x along the crack and that at which the gas strikes the inlet, i.e.,

$$K' = \left(1 + \frac{3Hx}{16A} \right)^{-1}$$

Substituting for K' and integrating (1) we obtain

$$t_1 = \int_0^{t_1} dt = \frac{H}{f A \nu_1} \int_0^{\ell_1} \left(1 + \frac{3Hx}{16A} \right) dx$$

i.e.,

$$t_1 = \frac{H \left(16A \ell_1 + \frac{3H \ell_1^2}{2} \right)}{16A^2 \nu_1 f} = \frac{G}{\nu_1 f} \qquad \dots \dots \quad (2)$$

where G is a geometrical factor and equal to H $(16A \ell_1 + 3H \ell_1^2/2/16A^2$

Alternatively

$$t_1 = \frac{G \, (MT)^{1/2}}{3.5 \times 10^{22} \, Pf} \qquad \cdots \qquad (3)$$

where P is the pressure in mm Hg, M is the molecular weight and T is the absolute temperature.

Thus for a given temperature and gas, t_1 depends directly on the geometrical factor G and inversely on ν_1 and P. It is evident that equation (2) becomes identical with the expression for t'_1 originally obtained by Clausing[8] for the time to cover the walls of a cylindrical pore when $A = \pi a^2$ and $H = 2 \pi a$, where a is the radius of the pore, i.e.,

$$t'_1 = \frac{16 \, a \, \ell_1 + 3 \, \ell_1^2}{8 \, a^2 \, \nu_1 \, f} \qquad \cdots \qquad (4)$$

for $a \ll \ell_1$.

As a numerical example, the time is estimated for the walls of a crack of uniform rectangular section (a x b) to be covered with a uni-molecular layer of oxygen. For a channel with a rectangular section, $G = 2 \ell_1 (1/a + 1/b) + 3/8 \, \ell_1^2 (1/a + 1/b)^2$. In practice, a crack would resemble a narrow slit with one dimension of the crack opening significantly larger than the other, i.e. the width, a, will be small compared with the other dimension, b. In this case, G can be approximated by $G \sim 3 \, \ell_1^2 /8a^2$. Taking $a \simeq 10^{-5}$ cm, $\ell_1 \simeq 10^{-2}$ cm and $f = 16 \times 10^{-16}$ cm^2 for oxygen, $t_1 \simeq 0.6 \, P^{-1}$ sec. For oxygen pressures ranging from 10 to 10^{-6} mm Hg, t_1 varies from 6×10^{-2} sec to 6×10^5 sec; i.e., at low pressures the time t_1 is appreciable and can be comparable with test times. The above treatment is in accord with the phenomenon of delayed fracture where the fracture time varies between 10^{-2} to 10^7 sec and is drastically affected by the normal air atmosphere[1].

The above discussion...

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